Hydroprene Prolongs Developmental Time and Increases Mortality in Wandering-phase Indianmeal Moth (Lepidoptera: Pyralidae) Larvae

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ABSTRACT Wandering phase Indianmeal moth, *Plodia interpunctella* (Hübner), larvae were exposed to the label rate of hydroprene (1.9×10^{-3} mg [AI]/cm^2) sprayed on concreted petri dishes. Larvae were exposed for 1, 3, 6, 12, 18, 24, and 30 h and maintained at 16, 20, 24, 28, and 32°C and 57% RH until adult emergence. Larval developmental time and mortality were significantly influenced by temperature and exposure intervals. Maximum developmental time (47.2 ± 1.3 d) occurred at 16°C, and the minimum developmental time (7.0 ± 0.5 d) occurred at 32°C. Larval mortality generally increased at all of the five tested temperatures as exposure period increased. The greatest mortality (82.0 ± 0.1%) occurred when larvae were exposed for 30 h at 28°C, and minimum mortality (0.0 ± 0.5%) occurred at 16°C when larvae were exposed for 1 h. The relationships between temperature, exposure period, and developmental time were described by polynomial models, based on lack-of-fit tests. Hydroprene has potential to be an effective alternative to conventional insecticides in surface treatments for Indianmeal moth management. Response-surface models derived from this study can be used in simulation models to estimate the potential consequences of hydroprene on Indianmeal moth population dynamics.

KEY WORDS *Plodia interpunctella*, Indianmeal moth, development, mortality, insect growth regulator

Indianmeal moth, *Plodia interpunctella* (Hübner), is a serious cosmopolitan pest of stored commodities such as raw, packaged, and animal foods (Cox and Bell 1991, Campbell et al. 2002), and it has been recorded infesting >83 kinds of stored food (Richards and Thomson 1932, Deso 1976). Indianmeal moth larvae continuously spin silken webbing and feed from within the webbing. The webbing contains larval cast skins and frass, which impart an unpleasant odor to the infested commodity. Larval infestation found in packaged food leads to immediate rejection and erodes consumer confidence in the product. In grain bins, the surface layer can be covered with a thick mat of webbing, which renders chemical treatments difficult or at times impossible to apply. All five larval stages of Indianmeal moth move and feed within the infested commodity. However, the fifth instars, called the wandering phase larvae, are especially important economically because they often leave the infested commodity and wander in search of a suitable pupation site. The distance traveled by these larvae is so great that when the adults emerge sometimes away from their feeding sites, they are sometimes confused with clothes moths, such as the webbing clothes moth, *Tineola bisselliella* (Hummel); the casemaking clothes moth; *Tinea pellionella* (L.); or the carpet moth, *Trichophaga tapetzella* (L.) (Smith 2000). Due to this wandering nature, fifth instars are suitable candidates for management by using surface insecticidal applications.

Hydroprene is a juvenile hormone analog registered for stored-product pest management in the United States, and it can be used for surface treatments. Surface treatment with hydroprene is a common management practice in food processing and storage facilities such as retail stores, warehouses, and flour mills. Hydroprene also can be used in aerosol and impregnated disc applications. Hydroprene is an alternative to conventional insecticides, many of which are being reevaluated or facing threat of removal because of new regulatory laws and interpretation of existing laws. Hydroprene is classified as a biopesticide because of its virtually nontoxic nature toward vertebrates, rapid biodegradability, and specific activity against insects. There are several reports of the effects of hydroprene on household pests, especially cockroaches (Bennett et al. 1986; King and Bennett 1988, 1989, 1990; Reid and Bennett 1994; Edwards et al. 1995; Kaakeh et al. 1997; Stoltzman and Stay 1997; Bell et al. 1999), and some of these studies involved spraying hydroprene on floors to control cockroach popula-

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tions. Many of the earlier studies on hydroprene with stored-product insect pests were conducted with beetles (Loschiavo 1975, 1976; McGregor and Kramer 1975; Amos and Williams 1977; Rup and Chopra 1984), and relatively fewer studies were conducted with lepidopteran larvae (Nickle 1979, Stockel and Edwards 1981).

Arbogast et al. (2002) showed reduction in population of several stored-product pests, including the Indianmeal moth, when hydroprene was applied as a spot-treatment in a botanical warehouse. In the laboratory, exposing Indianmeal moth eggs to hydroprene sprayed on cemented petri dishes prolonged the egg developmental time and caused mortality in a dose-dependent manner (Mohandass et al. 2005). Timing of hydroprene application and assessment of its likely population consequences can be improved with the aid of simulation models of population dynamics (Hagstrum and Flinn 1990, Flinn and Hagstrum 1990, Flinn et al. 1997). Insecticide effectiveness is related to temperature (Scott 1995) and the length of exposure period (Arthur 2001). The objective of this study was to quantify the effects of hydroprene sprayed on concreted petri dishes on the development and mortality of wandering phase Indianmeal moth larvae. Equations derived from this and other studies will ultimately be incorporated into a population dynamics model for use in the management of Indianmeal moth.

Materials and Methods

Experimental Design. This experiment was set up as a split-plot design (Kuehl 2000), with five levels of temperature (16, 20, 24, 28, and 32°C) as the whole-plot factors and seven levels of exposure period to hydroprene (1, 3, 6, 12, 18, 24, and 30 h) as subplot factors. There were 35 treatment combinations in total. Six different incubators (ThermoForma, Marrietta, OH) were used as whole-plot experimental units, one each for each temperature, and cemented petri dishes were used as subplot units for individual exposure periods. Two response variables, Indianmeal moth developmental time and mortality, were quantified. To maintain 57% RH throughout the experiment, humidity chambers were created using plastic containers (26 by 36.5 by 15 cm) with a waffle-type plastic grid in the bottom. A saturated NaBr solution maintained humidity inside each plastic container (Greenspan 1977). Two containers, one each for treatments and controls, were placed in each incubator. Humidity was uniform across all of the whole and subplot treatments and therefore was not considered as part of the treatment design. Daily temperature and humidity inside the individual incubators were monitored by placing a HOBO (Onset Computer Corporation, Bourne, MA) inside each humidity container.

Experimental Arenas and Hydroprene Formulation. We applied hydroprene as a surface treatment on concrete because this is a common floor surface in warehouses, some retail stores, and other storage facilities throughout much of North America. Concrete (Rockite, Hartline Products Co., Cleveland, OH) was mixed in an approximate ratio of 3,200 g of concrete in 1,600 ml of water to a thick running consistency (Arthur 1999). The liquid slurry was then poured into individual petri dishes listed as 100- by 15-mm capacity. However, the area of the top and bottoms of these dishes was 63.6 and 62 cm^2, respectively. In total, 190 petri dish arenas were prepared by pouring concrete to approximately one-half the capacity of the top and the full capacity of the bottom of the dish. All concrete arenas were dried for ≈48 h at room temperature (27°C).

The hydroprene formulation used in the study was Gentrol (9.0% active ingredient [AI], ≈90 mg [AI]/ml). Label directions specify application by mixing 1 oz in 1 gallon of water to cover 1,500 ft^2 (29.57 ml in 3.79 liters of water to cover 134.8 m^2), which is 1.9×10^{-3} mg [AI]/cm^2. The area of the bottom of the concrete petri dish was 62 cm^2, so the volume of spray needed for this area was 0.17 ml. This amount was too small to formulate individual concentrations. We prepared the hydroprene concentrations by mixing 0.38 ml of Gentrol in 50 ml of distilled water and thoroughly shaking the solution. In total, five replicates were done in a series of three blocks; however, separate hydroprene solutions were prepared for each of the five replicates.

For the first replicate, one untreated control dish set (top and bottom) for each temperature (five total) were prepared by spraying both halves of the concrete

Table 1. Equations describing 1) relationship between temperature, exposure interval, and developmental time; and 2) relationship between temperature, exposure interval, and mortality for wandering phase Indianmeal moth larvae exposed to hydroprene

	Estimate	*t*	*P*	Adjusted R^2
1) Developmental time (d)				
a	61.0 ± 1.14	53.2	<0.01	
b	−1.7 ± 0.05	−35.9	<0.01	
c	−0.3 ± 0.07	4.8	<0.01	
d	0.002 ± 0.003	0.7	0.48	0.87
2) Mortality (%)				
a	−1.04 ± 0.4	−2.5	0.01	
b	0.11 ± 0.02	6.5	<0.01	
c	0.06 ± 0.03	2.3	0.02	
d	0.005 ± 0.001	4.9	<0.01	

a = intercept, b = temperature (°C), c = exposure interval (h), and $d = b(c)$. All models were computed with df = 3, 171 and are of the form y (developmental time (or) mortality) $= a + b + c + d$.

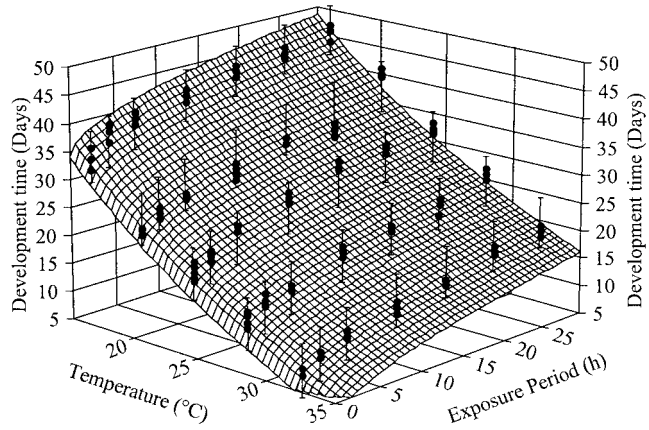

Fig. 1. Response-surface model for wandering phase Indianmeal moth larval developmental time. This model was chosen based on highest F value (2,999; df = 3, 172) and is in the form $lnz = a + blnx + cy^{0.5}$, where $a = 138.19 \pm 1.73$, $b = -38.19 \pm 0.54$, $c = 2.65 \pm 0.08$, x = temperature (°C), y = exposure period (h), and z = larval developmental time (days). Adjusted $R^2 = 0.97$.

arenas with distilled water, using an artist's airbrush (no. 100 LG, Badger Air Brush Co., Franklin Park, IL). The liquid was sprayed by holding the airbrush ≈5–10 cm above the treatment arenas and by slowly releasing pressure until all of the material was dispensed. Both the tops and the bottom were treated in this manner. For the treatment, 35 dish sets (seven exposures × five temperatures) were treated by spraying 0.17 aliquots of the hydroprene solution onto each of the top and bottom arenas. In the next two series of replicates, two treated replicates were created as described above, along with an untreated control, for a total of five replications (15 control dish sets with 175 treated dish sets). However, separate insecticide solutions were prepared for each of the five replicates, as described above.

Insects. Fifth instars of Indianmeal moth were obtained from an insecticide-susceptible laboratory strain, which is a mixture of several field-collected strains maintained at the USDA Grain Marketing and Production Research Center, Manhattan, KS. The Indianmeal moth larval voucher specimen (no. 167) is located in the Museum of Entomological and Prairie Arthropod Research, Kansas State University, Manhattan, KS. All cultures are reared inside incubators set at 27°C and 60% RH. Before setting up the experiment, Indianmeal moth larvae reared inside a 3.8-liter jar were placed on a tray by carefully transferring them, along with the laboratory media, by using a spatula. Ten actively wandering fifth instars were then transferred to each of the treated and untreated petri dishes by using a featherweight forceps (Bioquip, Rancho Dominguez, CA). Larvae were held in between a sandwich of the two cemented petri dishes placed on top of each other with opposing sides facing each other. The bottom dish was completely filled with concrete and the top dish was only half-filled, which resulted in maximum hydroprene exposure to the lar-

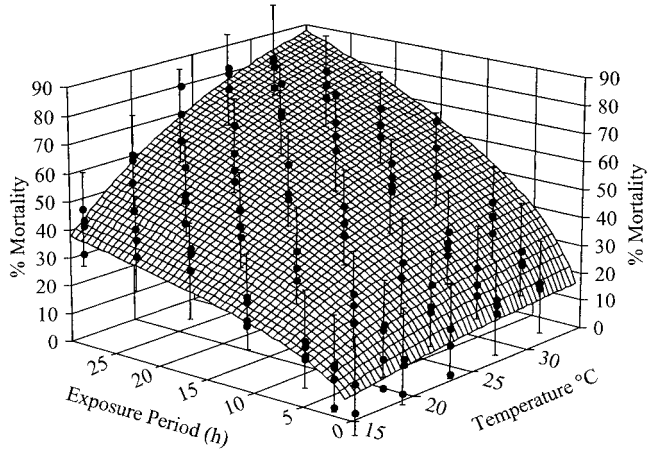

Fig. 2. Response-surface model for wandering phase Indianmeal moth larval mortality. This model was chosen based on highest F value (975; df = 3, 172) and is in the form $lnz = a + blnx/x^2 + clny$, where $a = 3.22 \pm 0.05$, $b = 91.8 \pm 5.0$, $c = 0.44 \pm 0.01$, x = temperature (°C), y = exposure period (h), and z = % larval mortality. Adjusted $R^2 = 0.97$.

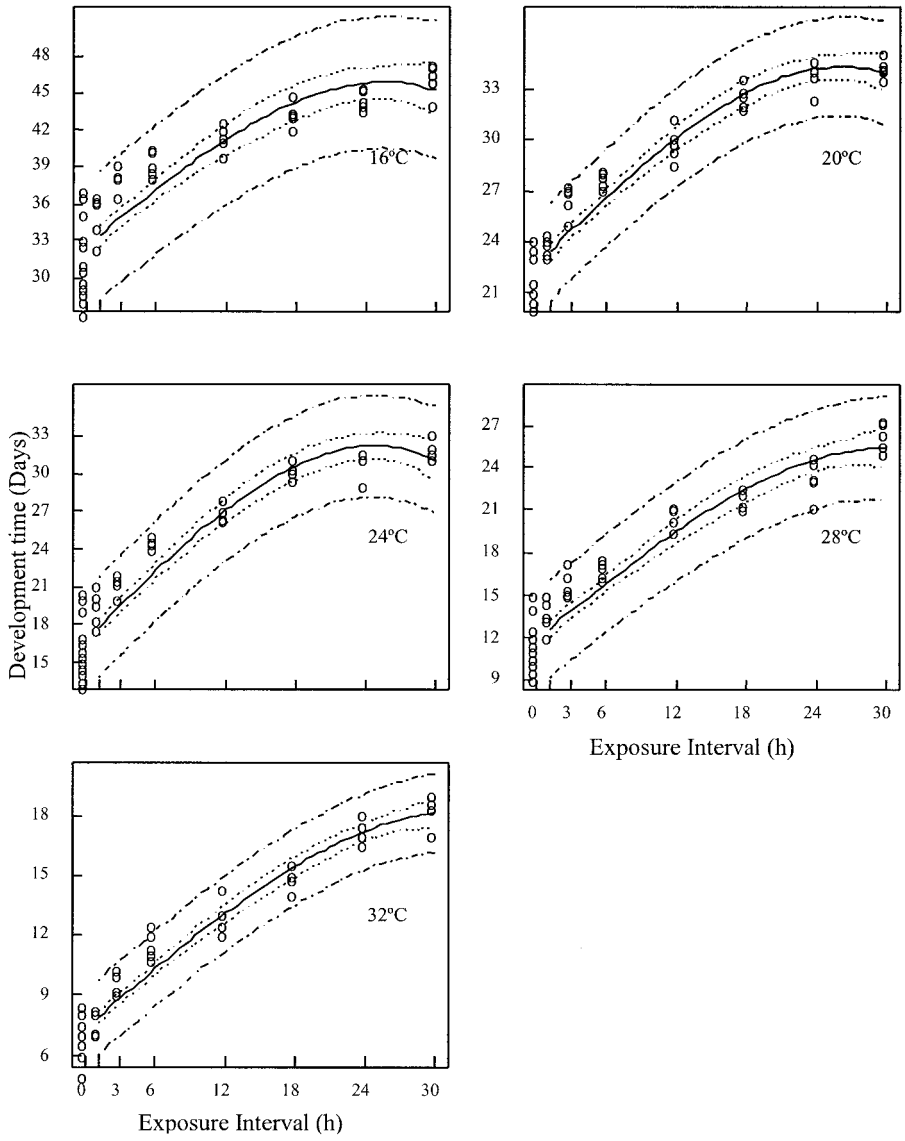

Fig. 3. Duration of development of wandering phase Indianmeal moth larvae exposed to hydroprene at various temperatures for different exposure periods. Regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

vae while allowing them to move freely within the available space. Randomization for subplot treatments was done by randomly selecting a pair of concrete arenas for each exposure period. The arenas, along with the larvae, were sealed by using scotch tape and placed inside a humidity container inside individual temperature incubators. The untreated controls were held inside the second container for the maximum exposure period of 32 h. Upon completion of the individual exposure intervals, the larvae from the treated dishes were removed randomly from each treatment combination and placed on top of sterile filter paper inside new individual, pesticide-free plastic petri dishes. The treatment concrete dishes were discarded, and the dishes containing larvae were sealed and placed back in the same humidity chambers. The number of emerging adults inside each petri dish was recorded every 24 h for 50 d, and after 50 d larvae that had not emerged as adults were considered as either dead or arrested by exposure to hydroprene.

Data Analysis. Regression models were used to evaluate impacts of temperature and hydroprene exposure period on developmental time. Kramer et al. (1991) showed that erroneous predictions could occur in least-square estimations when model parameters are estimated by using some modified form of data, such as rate (1/developmental time). Minimizing the squared error for developmental rate is not the same

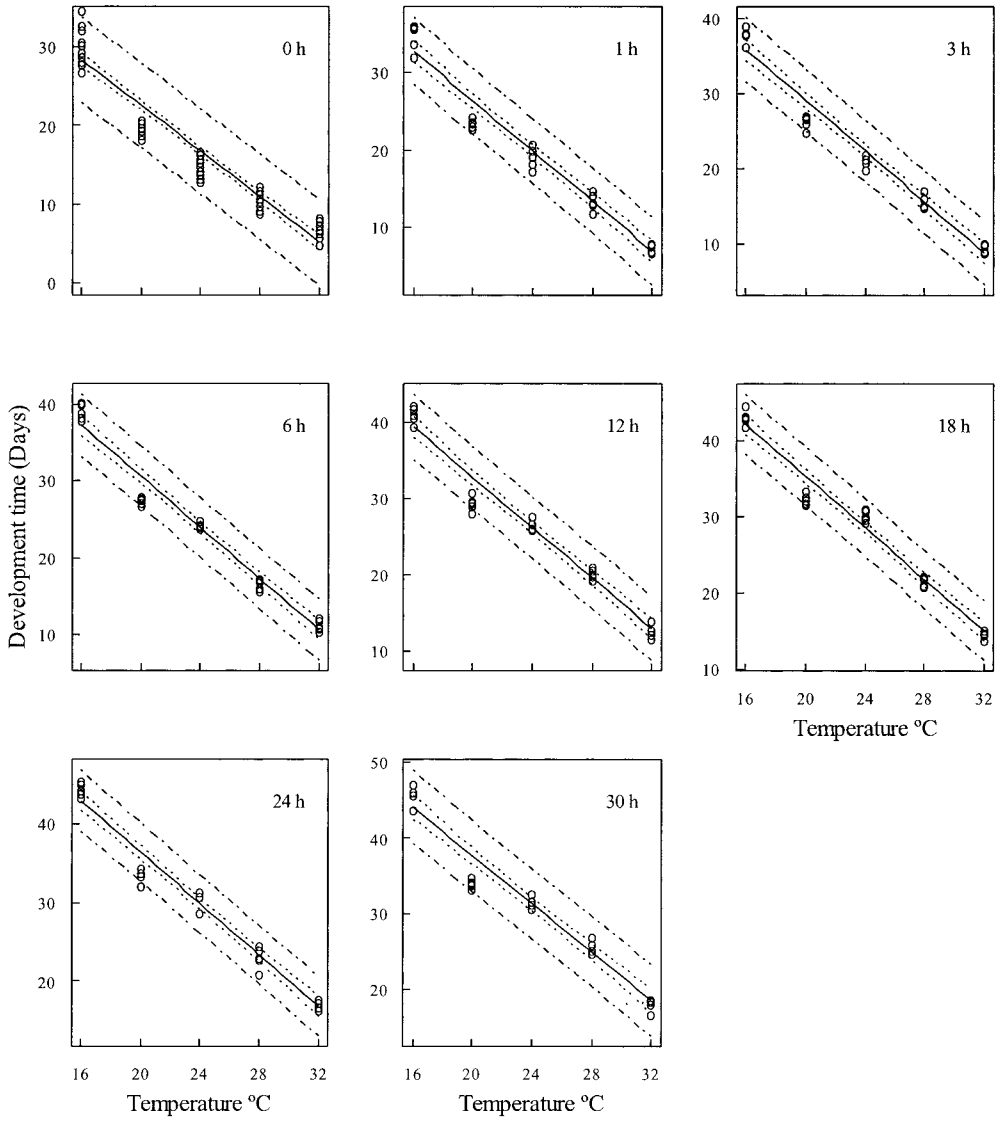

Fig. 4. Duration of development of wandering phase Indianmeal moth larvae exposed to hydroprene for various periods at different temperatures. Regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

as minimizing the squared error for developmental time, especially in the longer developmental time range. We used time instead of rate to fit all our regression models for larval developmental time. The regression models for developmental time were chosen based upon lack-of-fit-tests, but not R^2 or adjusted R^2 values, which are traditionally considered to be standards for model selection. Because this is a designed experiment and the observations are derived from replicated units, it was possible to conduct lack-of-fit tests by partitioning the residual sum of squares into lack-of-fit and pure error components (Weisberg 1985). This involved determining the part of the residual sum of squares that can be predicted by including additional terms for the predictor variables in the model, such as higher order polynomial terms, and the part of the residual sum of squares that cannot be predicted by any additional terms, i.e., the sum of squares for pure error. A test of lack-of-fit for the model without the additional terms was then performed, using the mean square pure error as the error term. This provided a sensitive test of model fit because the effects of the additional higher order terms were removed from the error. Care was taken to fit models that were biologically reasonable and described data adequately (Throne 1994, Faraway 1994).

Appropriate models for individual data sets were selected by computing comparisons made between the desired and saturated models with higher order

Table 2. Equations describing relationships between temperature or exposure interval and developmental time for wandering phase Indianmeal moth larvae exposed to hydroprene

	$a \pm$ SE	$b \pm$ SE	$c \pm$ SE	$d \pm$ SE	Adj. R^2	Lack-of-fit P
Temp (°C)						
16	33.3 ± 0.5	0.49 ± 0.03			0.75	<0.01
	32.4 ± 0.5	1.02 ± 0.11	−0.01 ± 0.004		0.82	<0.01
	31.9 ± 0.4	1.79 ± 0.24	−0.10 ± 0.022	0.002 ± 0.0005	0.85	0.06
20	23.3 ± 0.3	0.43 ± 0.02			0.86	<0.01
	22.6 ± 0.3	0.83 ± 0.06	−0.02 ± 0.003		0.95	0.04
	22.4 ± 0.3	1.09 ± 0.14	−0.04 ± 0.013	0.0006 ± 0.0003	0.92	0.10
24	17.7 ± 0.4	0.56 ± 0.03			0.83	<0.01
	16.6 ± 0.3	1.20 ± 0.09	−0.023 ± 0.003		0.92	<0.01
	16.3 ± 0.3	1.70 ± 0.18	−0.073 ± 0.016	0.0011 ± 0.0004	0.93	0.05
28	12.4 ± 0.3	0.49 ± 0.02			0.88	<0.01
	11.8 ± 0.3	0.82 ± 0.08	−0.012 ± 0.003		0.91	<0.01
	11.4 ± 0.3	1.38 ± 0.15	−0.067 ± 0.014	0.0012 ± 0.00032	0.93	0.25
32	7.7 ± 0.2	0.38 ± 0.01			0.93	<0.01
	7.3 ± 0.2	0.58 ± 0.04	−0.008 ± 0.002		0.95	<0.01
	7.2 ± 0.2	0.78 ± 0.10	−0.026 ± 0.008	0.0004 ± 0.0002	0.95	0.07
Exposure (h)						
0	51.5 ± 1.2	−1.44 ± 0.05			0.90	<0.01[a]
1	58.6 ± 1.7	−1.61 ± 0.07			0.95	<0.01[a]
3	62.9 ± 1.7	−1.69 ± 0.07			0.96	<0.01[a]
6	63.7 ± 1.6	−1.65 ± 0.06			0.96	<0.01[a]
12	65.8 ± 0.5	−1.64 ± 0.07			0.96	<0.01[a]
18	70.1 ± 1.2	−1.72 ± 0.05			0.98	<0.01[a]
24	68.2 ± 1.8	−1.60 ± 0.07			0.95	<0.01[a]
30	69.6 ± 1.9	−1.59 ± 0.08			0.94	<0.01[a]

a, b, c, $d = \hat{\beta}_0$, $\hat{\beta}_1 e$, $\hat{\beta}_2 e^2$, $\hat{\beta}_3 e^3$, respectively, for developmental time models within temperatures and $\hat{\beta}_0$, $\hat{\beta}_1 t$, $\hat{\beta}_2 t^2$, $\hat{\beta}_3 t^3$, respectively, for developmental time models within exposure intervals. All models are of the form y (developmental time) $= a + bx + cx^2 + dx^3$, where x is either temperature or exposure period. All simple linear regression models within temperatures were computed with df = 1, 23; all quadratic models with df = 2, 22; and all cubic models with df = 3, 21. All simple linear models within exposure periods were computed with df = 1, 54.

[a] Although lack-of-fit for simple linear models was significant, higher order models that fit the data more closely were less biologically reasonable for these data.

polynomial terms by way of F-testing methodology (Faraway 1994). Influential observations in the data set were checked by using Cook's distance plots. Nonconstant variance (heteroscedascity) and nonlinearity were checked by plotting residuals for the selected models (Faraway 1994). The strengths of the regression relationships were measured by their adjusted R^2 values (Seber 1977), and 95% confidence intervals on the mean and prediction intervals were plotted for individual equations (Becker et al. 1988, Murrell 1999).

Analysis of variance (ANOVA) computation (Chambers et al. 1992) in R version 1.9.0 for Windows (R Foundation for Statistical Computing, Vienna, Austria) (Ihaka and Gentleman 1996, R-Development Core Team 2004) showed no significant interaction effect between temperature and exposure period on developmental time, but there was a significant interaction on percentage mortality (Table 1). The effects of hydroprene on larval developmental time and mortality were modeled by fitting three-dimensional (3D) response surface models by using temperature and exposure periods as predictor variables in TableCurve 3D (SYSTAT Software Inc., Point Richmond, CA) (Figs. 1 and 2). Such 3D models, especially when they are static and presented in black and white, are difficult to interpret (Merwin et al. 1994) and offer less quantitative information to a scientific reader than two-dimensional graphs. Therefore, for our data, the percentage of larval mortality and developmental time were plotted and regressed individually within different temperatures and exposure periods using R.

Results

Developmental Time. Within each temperature, the number of days taken for wandering-phase larvae to emerge as adults generally increased with increase in exposure period to hydroprene (Fig. 3), and within each exposure period, the developmental time decreased as temperature increased (Fig. 4). A cubic model was fit to the data for each temperature, and a simple linear model was fit to the data for each exposure period (Table 2). The longest developmental time among the treatments of 47.2 ± 1.3 d occurred at 16°C when the larvae were exposed for 30 h, whereas the shortest developmental time of 7.0 ± 0.5 d occurred when the larvae were exposed for 1 h at 32°C. Longest developmental time in the untreated controls was 32.2 ± 1.0 d at 16°C, and the shortest developmental time was 7.0 ± 1.0 d at 32°C.

Mortality. Among treatments, the greatest mortality occurred when larvae were exposed for 30 h at 28°C, whereas the minimum mortality occurred at 16°C when larvae were exposed for 1 h. Quadratic equations adequately fit the data at all temperatures when percentage mortality was regressed on exposure interval (Fig. 5; Table 3). When percentage mortality was regressed on temperature (Fig. 6; Table 3), simple linear equations fit the data at 1, 3, 6, 12, and 24 h, and

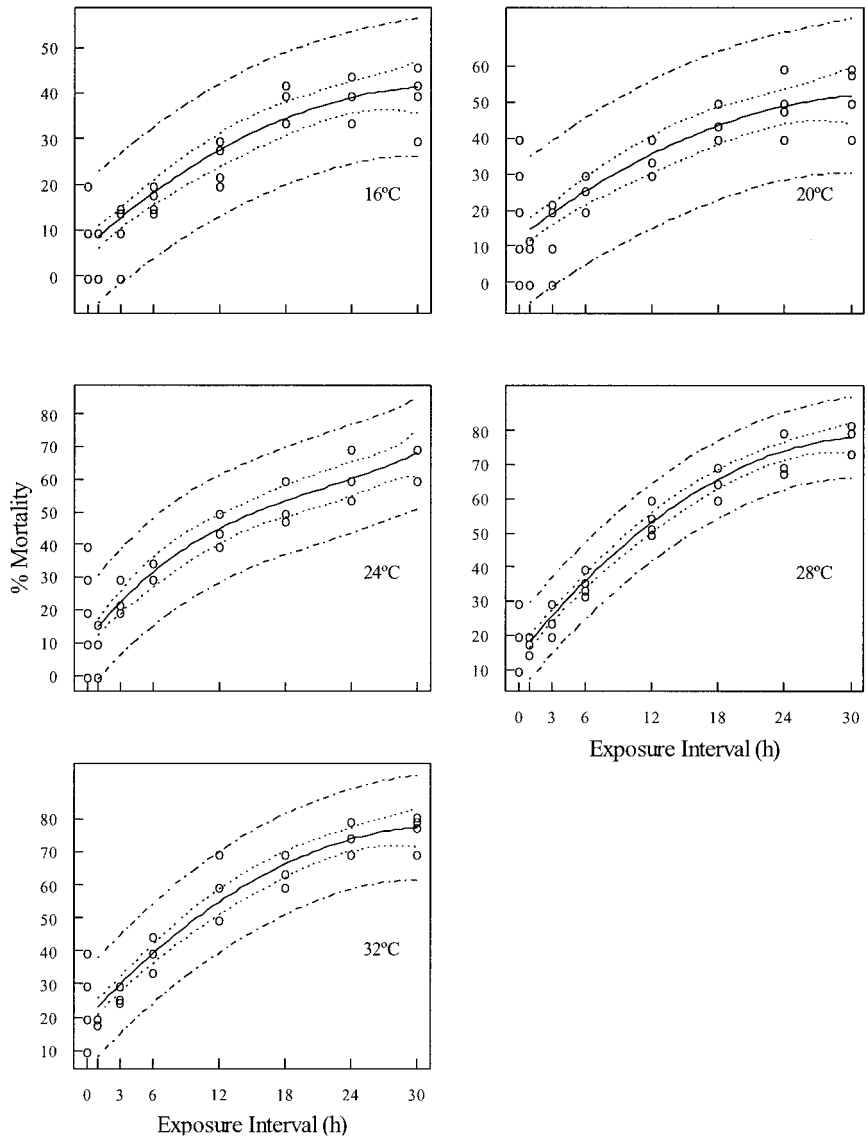

Fig. 5. Percentage mortality of wandering phase Indianmeal moth larvae exposed to hydroprene at various temperatures for different exposure periods. Regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

a quadratic model fit the data at 30 h. However, at 18 h, higher order polynomial models, including a cubic model, showed significant lack-of-fit. Among the untreated controls, there was no significant effect of temperature on mortality ($F = 0.5$; df = 3, 101; $P = 0.6$). The mortality in untreated controls averaged 16.8 ± 11.2% and ranged between 0 and 40% (Fig. 6).

We did not expect a nonlinear trend for mortality at the 18-h exposure period because simple linear models adequately fit the data at most of the other exposure periods below 30°C. Adding a cubic term to the quadratic model did not change the lack-of-fit (Table 3). Therefore, we checked for the presence of influential data points within the 18-h-exposure data set (Faraway 1994). Cook's distance plot for this data set revealed that two data points were considerably farther away from the others, and when these were removed and a simple linear model was refit to the data set, there was no significant lack-of-fit (Fig. 7).

Discussion

The mean control mortality across all temperatures was only 13.6 ± 10.4%, but was 40% in one replicate each at 20 and 32°C. However, control mortality in most of the observations ranged between 10 and 20%, which seems high but reasonable because we were using late instars. Handling these larvae produced

Table 3. Equations describing relationships between temp or exposure interval and percentage mortality for wandering phase Indianmeal moth larvae exposed to hydroprene

	$a \pm$ SE	$b \pm$ SE	$c \pm$ SE	$d \pm$ SE	Adj. R^2	Lack-of-fit P
Temp (°C)						
16	7.9 ± 13	1.27 ± 0.10			0.76	0.01
	6.4 ± 1.3	2.15 ± 0.33	−0.033 ± 0.012		0.78	0.08
20	13.9 ± 1.8	1.43 ± 0.13			0.68	0.01
	12.3 ± 1.9	2.35 ± 0.47	−0.034 ± 0.017		0.69	0.24
24	13.5 ± 1.50	2.00 ± 0.11			0.85	<0.01
	11.3 ± 1.5	3.30 ± 0.37	−0.048 ± 0.013		0.87	0.17
28	17.1 ± 1.2	2.33 ± 0.10			0.91	<0.01
	14.3 ± 1.0	3.97 ± 0.26	−0.061 ± 0.001		0.95	0.88
32	22.0 ± 1.5	2.12 ± 0.11			0.87	<0.01
	19.4 ± 1.4	3.61 ± 0.35	−0.056 ± 0.012		0.90	0.80
Exposure (h)						
1	−14.9 ± 4.6	1.08 ± 0.18			0.58	0.15
3	−9.8 ± 5.6	1.23 ± 0.22			0.53	0.20
6	−3.4 ± 3.2	1.40 ± 0.13			0.82	0.09
12	−4.7 ± 5.6	1.97 ± 0.22			0.76	0.57
18	9.0 ± 4.4	1.88 ± 0.17			0.82	0.03
	−3.1 ± 21.2	2.95 ± 1.83	−0.02 ± 0.01		0.92	0.02[a]
	206.0 ± 113.1	−24.93 ± 14.98	1.17 ± 0.64	−0.16 ± 0.0003	0.92	0.03[a]
	6.9 ± 4.2	1.99 ± 0.17			0.85	0.05[b]
24	3.2 ± 5.6	2.27 ± 0.22			0.80	0.24
30	1.6 ± 7.2	2.60 ± 0.29			0.76	<0.01
	−95.5 ± 27.8	11.17 ± 2.40	−0.17 ± 0.049		0.84	0.11

$a, b, c, d = \hat{\beta}_0, \hat{\beta}_1 e, \hat{\beta}_2 e^2, \hat{\beta}_3 e^3$, respectively, for mortality models within temperatures and $\hat{\beta}_0, \hat{\beta}_1 t, \hat{\beta}_2 t^2, \hat{\beta}_3 t^3$, respectively, for mortality models within exposure periods. All models are of the form y (developmental time) $= a + bx + cx^2 + dx^3$, where x is either temperature or exposure period. All simple linear regression models within temperatures were computed with df = 1, 22 and all quadratic models with df = 2, 21. All simple linear models within exposure periods were computed with df = 1, 54; all quadratic models with df = 2, 53; and all cubic models with df = 3, 52.

[a] Although the lack-of-fit test for the quadratic and cubic models yielded significant results, higher order models that fit the data more closely were not biologically reasonable for these data.

[b] Parameter estimates for regression equation without data points 23 and 24. These estimates were derived with df = 1, 20.

some control mortality, and the unusually high mortality in a couple of observations is most likely random chance or random variation and not due to any external factors.

Percentage of larval mortality data reported in this study can be analyzed using probit analysis (Throne et al. 1995) and can be used to estimate the toxicity and/or relative potency of hydroprene compared with other conventional insecticides used for surface spray. Detailed procedure for this kind of analysis can be found in Hubert (1992). However, we fit regression equations to the data so that they can be used in a population dynamics simulation model for Indianmeal moth that is currently being developed in our laboratory. The regression equations for developmental time and mortality derived in this and other bioassays can be directly used in a simulation program, which will help a pest manager determine the timing of hydroprene application and estimate the effectiveness of hydroprene on Indianmeal moth populations.

We fit simple linear equations to the data for developmental time within each exposure period. On looking at the scatter plot of the data, all observations except for the ones at 20°C aligned in a linear manner, whereas the observations at 20°C were consistently below the linear trend. One possible explanation for this could be a sudden increase in volatility of hydroprene at 20°C (Atkins et al. 1998) and a steady increase in volatility at temperatures above this range. However, we could not find a reasonable hypothesis for why this change in volatility would result in the pattern observed. Given the lack of reasoning, for the nonlinear trend, we fit simple linear equations to developmental time within each exposure period despite the lack-of-fit. Another possible explanation for the lack of may be that there was low-temperature inhibition at 16°C and then linear development above 16°C; however, we did not have enough data to fit a four-parameter model that included low-temperature inhibition.

We previously quantified the effects of hydroprene-treated concrete surfaces on the development and mortality of Indianmeal moth eggs (Mohandass et al. 2005). These studies show that hydroprene sprayed as a surface treatment significantly delays developmental time of eggs and larvae and decreases egg hatch and emergence of adults when exposed as wandering phase larvae. Treating concrete floor surfaces with hydroprene in food storage facilities may be an effective alternative to conventional insecticides. In the future, stored-product pest management will consist more of a combined approach rather than dependence on a few chemical insecticides (White 1992, Arthur and Phillips 2003). Management strategies that combine tactics have been shown to be effective for control of other post-harvest Lepidopteran pests (Johnson et al. 1998, 2002). One or more of the hydroprene application methods, such as a surface spray application, crack-and-crevice treatment, application as a fog, or as impregnated discs, may be used in combination management strategies for Indianmeal moth control.

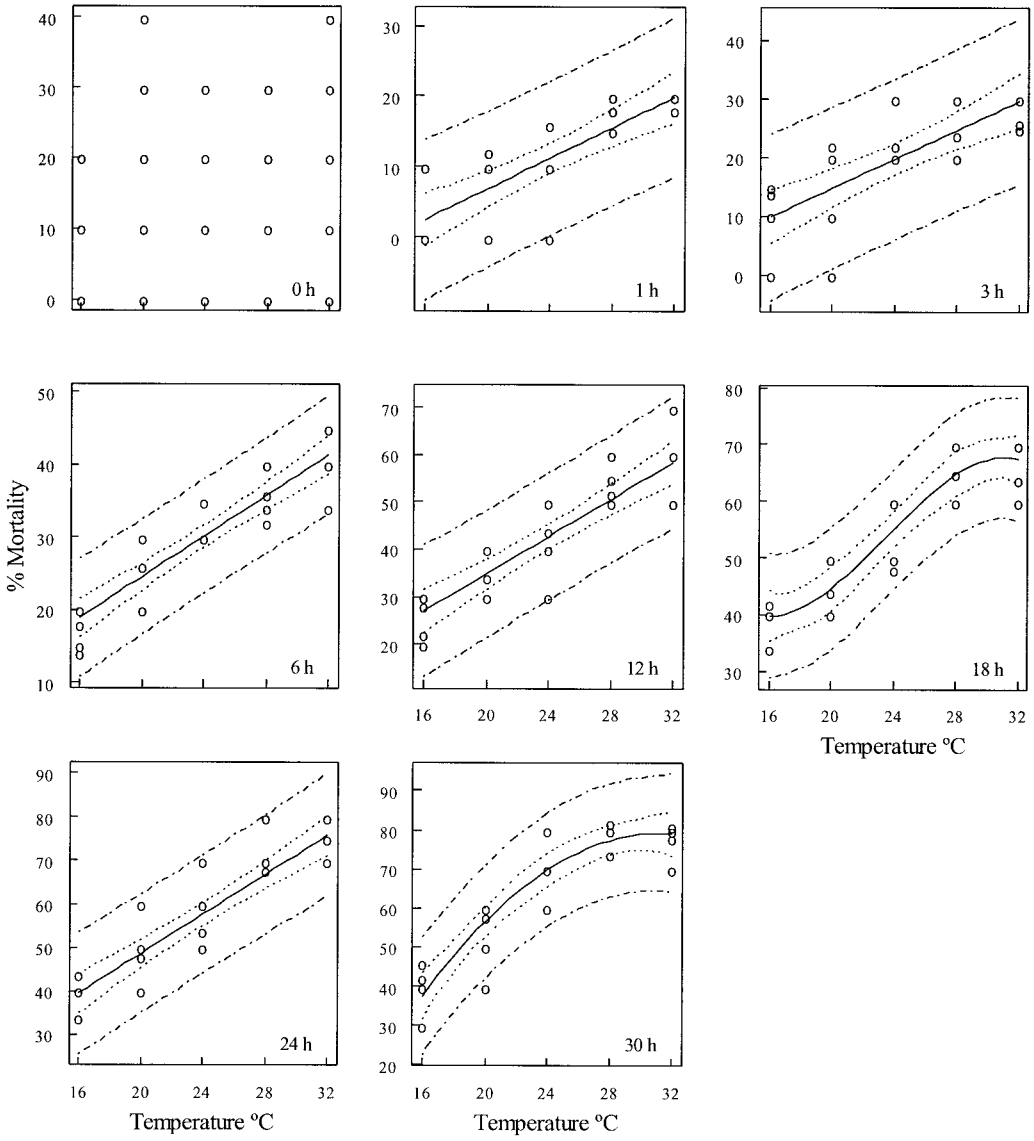

Fig. 6. Percentage mortality of wandering phase Indianmeal moth larvae when exposed to hydroprene for various periods at different temperatures. Regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

We tested only one mode of hydroprene application, surface application, and on one specific floor surface, concrete. Tests with other insect growth regulators (IGRs) have shown varied effects of hydroprene on different flooring surfaces. Atkins et al. (1998) showed that absorbent surfaces such as unfinished plywood, fiberboard, and vinyl tile had more activity on the mortality of German cockroach nymphs than their nonabsorbent counterparts such as glass, stainless steel, ceramic tile, and formica. Hydroprene-treated stainless steel surfaces had less residual activity than masonite and unpainted plywood (Kaakeh et al. 1997). Differences in the persistence or residual activity of hydroprene may differ from one type of surface to another. Nevertheless, these studies and our own study indicate that hydroprene can be used for surface treatments in facilities having concrete flooring surfaces.

Resistance by insects to other IGRs has been cited in the literature (Dame et al. 1998; Cornel et al. 2000, 2002); therefore, necessary steps to slow resistance development by insects to hydroprene should be devised and followed. Insects may evade a lethal dose of hydroprene when applied only as a surface treatment; therefore, alternating the use of several of the hydroprene application methods could slow insect resistance development. Another possible method to slow resistance development is by timing and targeting of

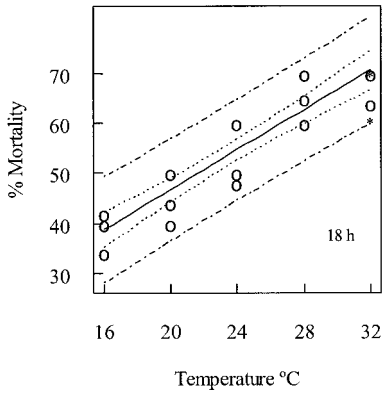

Fig. 7. Regression equation for percentage mortality at 18-h exposure without observations 23 (* at 70% mortality) and 24 (* at 60% mortality). Regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

hydroprene application toward specific life stages of Indianmeal moth, at least in storage facilities where overlapping generations do not occur.

Other IGRs may possess toxicity to Indianmeal moth and should be evaluated against different life stages. Methoprene and pyriproxifen recently have been labeled as aerosol treatments and for some surface applications, and they also should be tested for their effects on Indianmeal moth. More studies are needed to find alternative chemicals that can be used in rotation with hydroprene in stored-product environments.

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